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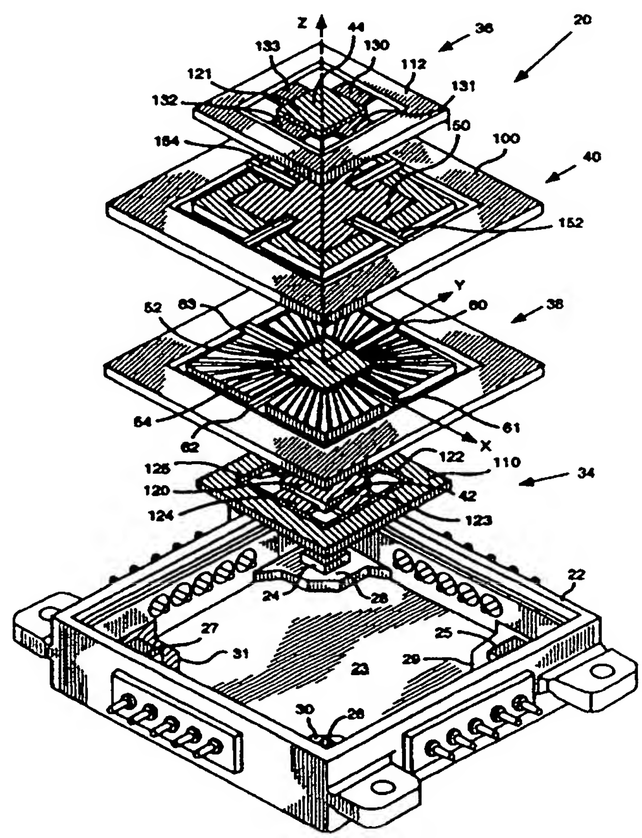
(54) Title: TWO AXIS NAVIGATION GRADE MICROMACHINED ROTATION SENSOR SYSTEM

(57) Abstract

A two axis closed loop angular rate sensor which provides a digital delta theta output signal. A drive member is formed of a single, silicon wafer having a pair of oppositely-facing planar surfaces. The drive member includes a frame and a drive member central portion connected to the frame and arranged to have rotational compliance between the frame and the central portion about an axis perpendicular to the planar surfaces of the silicon wafer. Drive signals are applied to a plurality of electrodes on the central portion to cause rotational oscillation of the drive member central portion about a drive axis perpendicular to the planar surfaces of the silicon wafer. A silicon sensing member is connected to the drive member. The sensing member has a central support member connected to the drive member central portion such that rotational oscillations of the drive member central portion are transmitted to the sensing member central portion. A sensing portion is connected to the sensing member central support member to allow the sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the sensing portions. Signal processing apparatus is connected to the sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portion.



TWO AXIS NAVIGATION GRADE MICROMACHINED ROTATION SENSOR SYSTEM

BACKGROUND OF THE INVENTION

This invention relates generally to rotation sensors for use in applications such as navigation. In particular this invention relates to a rotation sensor system that provides high accuracy while operating in the high G, high vibration environment of reentry vehicles and the like. Still more particularly, this invention relates to a rotation sensor system based on a silicon chip that includes Coriolis acceleration sensors for measuring rotation rates about two orthogonal sensing axes.

Previously known micromachined Coriolis rotation sensor systems have demonstrated bias repeatability in the 10° to 1000°/hr range. Based on an analysis of these concepts, it does not appear credible that their performance could be improved by three to five orders of magnitude to produce a high-accuracy navigation grade device, while meeting the low cost and high reliability objectives presently set for the rotation sensor system of the present invention.

SUMMARY OF THE INVENTION

A rotation sensor design according to the invention incorporates many of the performance advantages of the tuned rotor gyro while exploiting the low cost and reliability benefits of micromachining. Essentially the rotation sensor may be visualized as a two-axis tuned rotor gyroscope except that the "rotor" angularly vibrates about the "spin axis", instead of steadily rotating about the spin axis. The angular momentum vector oscillates sinusoidally instead of remaining constant. The rotor is an inertially tuned sensing element, tuned to be resonant about its output axis at the oscillating frequency, instead of at spin speed.

The rotation sensor is a two axis closed loop angular rate sensor which provides a digital delta theta output signal. The micro-inertial rotation sensor according to the present invention is designed to support a 1 nm/hr navigation system while operating in the high G, high vibration environment associated with high lift-to-drag reentry vehicles and hypersonic submunitions. The rotation sensor according to the present invention is comprised of at least one solid state, micromachined sensing

element. The present invention is also designed to have small size and low weight, very low cost, low power, high reliability and for use in both commerical and militray applications.

A rotation sensor according to the invention comprises a base and a drive member mounted to the base and formed of a single, silicon wafer having a pair of oppositely-facing planar surfaces. The drive member includes a frame and a drive member central portion connected to the frame and arranged to have rotational compliance between the frame and the central portion about an axis perpendicular to the planar surfaces of the silicon wafer. The drive member furthyer comprises a plurality of electrodes formed on at least one side of the central portion and a drive apparatus for applying drive signals to the plurality of electrodes. The electrodes are arranged such that the drive signals cause rotational oscillation of the drive member central portion about a drive axis perpendicular to the planar surfaces of the silicon wafer.

The rotation sensor according to the invention further comprises a silicon sensing member that includes a sensing member central support member connected to the drive member central portion such that rotational oscillations of the drive member central portion are transmitted to the sensing member central portion. A sensing portion is connected to the sensing member central support member to allow the sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the sensing portions. Signal processing apparatus is connected to the sensing portion for producing a signal indicative of the input rotational rate as a function of the frequency of the out-of-plane oscillations of the sensing portion.

The rotation sensor according to the invention preferably further comprises a plurality of flexure beams connected between the frame and drive member central portion.

The rotation sensor according to the invention preferably further comprises a plurality of generally planar leaf spring members connected between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are

perpendicular to the planes of the leaf spring members. A capacative pickoff is preferably formed on the sensing portion such that the out-of-plane oscillations of the sensing portion produce capacitance changes in the capacitive pickoff.

The rotation sensor according to the invention preferably further comprises a plurality of base mounts connected between the base and the frame of the drive member. Each base mount is preferably formed to comprise a damped compliant element for providing a single mechanical resonant frequency in the rotation sensor and for attenuating external vibration inputs.

The signal processing apparatus may comprise a first summing circuit connected to the capacitive pickoff and arranged to receive signals indicative of the input rotation rate. A first modulation circuit may be connected to the first summing apparatus and arranged for modulating the input rotation rate signal with a signal indicative of the cosine of the drive signal frequency. A second modulation circuit may be arranged for modulating quadrature dynamic errors with a signal indicative of the sine of the drive signal frequency. A second summing circuit may be connected to add signals output from the first and second modulation circuits and provide feedback signals to the drive member. A first demodulator circuit may be connected to the capacitive pickoff for demodulating the sensor element response signal with the cosine of the drive frequency. A first compensation circuit may be connected to receive signal output form the first demodulator circuit, and a second demodulator circuit may be connected to the capacitive pickoff for demodulating the sensor element response signal with the sine of the drive frequency. A second compensation circuit may be connected to receive signal output form the second demodulator circuit. A first torquing modulator circuit may be connected to the first compensation circuit, and a second torquing modulator circuit may be connected to the second compensation circuit. The signal processing apparatus may still further include a third summing circuit for adding signals output from the first and second torquing modulator circuits, the third summing circuit producing a feedback signal that is input to the plurality of electrodes of the drive member.

A two axis rotation sensor according to the invention may also comprise pair of identical drive member/sensing portion combinations to mounted together in face-to-face relationship. Each drive member and sensing portion is formed in the manner described above. Drive signals cause the sensing portions to oscillate in opposite directions.

The signal processing apparatus preferably includes a first capacative pickoff formed on the sensing portion, such that the out-of-plane oscillations of the first sensing portion produce capacitance changes in the first capacitive pickoff, and a second capacative pickoff formed on the sensing portion, such that the out-of-plane oscillations of the second sensing portion produce capacitance changes in the second capacitive pickoff. The signal processing apparatus further comprises a first amplifier connected to the first sensign portion to amplify rotation response signals output therefrom and a second amplifier connected to the second sensign portion to amplify rotation response signals output therefrom. A first summing circuit is connected to the first and second amplifiers and arranged to produce a sum signal indicative of the sum of the amplified rotation signals. A second summing circuit is connected to the first and second amplifiers and arranged to produce a difference signal indicative of the difference of the amplified rotation signals. A modulation circuit is connected to the first and second summing circuits for providing in-phase and quadrature phase modulation of the sum and difference signals. A servo compensation circuit is connected to the modulation circuit for receiving in-phase and quadrature phase modulated sum and difference signals therefrom and producing a measured rate signal for input rotation about a first axis. An in-phase and quadrature phase torque modulation and summing circuit is connected to the servo compensation circuit to receive signals therefrom. An oscillator servo is connected to the in-phase and quadrature phase torque modulation and summing circuit and to the in-phase and quadrature phase demodulation circuit for providing automatic gain control. A third summing circuit is connected to the an in-phase and quadrature phase torque modulation and summing circuit for receiving a modulated signal therefrom;

An appreciation of the objectives of the present invention and a more complete understanding of its structure and method of operation may be had by studying the following description of the preferred embodiment and by referring to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is an exploded perspective view of a solid state two axis rotation sensor according to the present invention;

FIG. 1B is a perspective view of a rate sensing element that may be included in the rotation sensor of FIG. 1A;

FIG. 2 is a perspective view of a portion of a drive member that may be included in the apparatus of FIG. 1;

FIG. 3 is a cross-sectional view of a flexure beam that may be included in the apparatus of FIG. 2;

FIG. 4 is a bottom plan view of a drive member and sensor pickoff and torquing electrodes that may be included in the apparatus of FIG. 1;

FIG. 5 is a top plan view of the drive member of FIGS. 1 and 4;

FIG. 6 is a cross-sectional view taken along line 6—6 of FIG. 4 of a rotation sensor assembly that includes a capacitive signal pickoff that may be included in the apparatus of FIG. 1;

FIG. 7 schematically illustrates biasing and electrical signal pickoff for the apparatus of FIG. 6;

FIG. 8 illustrates circuitry for processing signals output from a Coriolis rotation sensor having each sensing element independently captured for each axis;

FIG. 9 is a block diagram illustrating additional features of the circuitry of FIG. 8; and

FIG. 10 is a generalized block diagram of circuitry for processing signals output from a Coriolis rotation sensor in which both sensing elements are combined in one capture loop for each axis.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring to FIG. 1A, a rotation sensor 20 according to the present invention includes a base 22 having a bottom cover 23 and a top cover (not shown) that is preferably essentially identical to the bottom cover 23. The base 22 has a generally rectangular cross section. The base 22

includes base mounts 24–27 mounted inside the base 22 at the corners 28–31, respectively.

The rotation sensor 20 comprises a pair of rate sensing members 34 and 36 that are preferably identical. Each of the rate sensing members 34 and 36 is preferably formed from a single silicon crystal by a micromachining process. The rotation sensor 20 further includes a pair of drive members 38 and 40 that are also identical and that also are each formed from single silicon crystals.

FIG. 1A shows opposite surfaces 42 and 44 of the rate sensing members 34 and 36, respectively. When the rotation sensor 20 is assembled, the surface 42 of the rate sensing member 34 is bonded to the lower surface of the drive member 38 as viewed in FIG. 1. Similarly, the lower surface of the rate sensing member 36 is bonded to the drive member 40.

The drive member 38 includes a peripheral frame 50 that is shown to be generally rectangular for convenience of illustration. The frame 50 may have other configurations. Referring to FIG. 2, central portion 52 of the upper surface 54 of the drive member 38 is thinner than the frame 50. Referring to FIGS 1 and 2, the central portion 52 has side edges 55–58 that are connected to the frame 50 by flexure beams 60–63. The flexure beams 60–63 preferably extend from the centers of the side edges 55–58 to the frame 50. In FIG. 2 part of the drive member 38 is omitted to show more clearly the central portion 52 and the flexure beams 60–63. FIG. 3 shows the cross section of the flexure beam 60 formed by etching the silicon crystal. The flexure beams 60–63 are preferably identical and have high resistance to bending in the vertical plane as viewed in FIGS. 1–3 and 6. The flexure beams 60–63 have low resistance to bending in the horizontal plane so that the central portion 52 may oscillate with a small amplitude rotational motion about a vertical axis through its geometric center.

Referring to FIGS. 1A and 5, four groups of electrode assemblies 70–73 are formed on the drive member 38 by appropriate doping of portions of the crystal that forms the drive member 38. The electrode assemblies are connected to the central portion 52 between the flexure

beams 60–63. Referring to FIG. 5, the cross hatched portions of the electrode assembly 70, for example, indicate the separate electrodes 80–88. The electrodes 80–88 are positioned with respect to the corner 90 of the electrode assembly 70 such that in the identical drive member 40, the corresponding electrodes are displaced angularly with respect to one another.

The displacement between the corresponding electrodes occurs as the identical drive member 40 is turned over and then arranged so that the electrode assemblies are face–to–face. The angular displacement of the electrodes in the two drive members 38 and 40 allows the electrodes to repel each other in an oscillatory manner at a frequency of twice the applied frequency, which causes oppositely directed rotational oscillations of the electrodes and corresponding central portions of the drive members. Electrical signal sources are connected to the two drive members to apply driving signals to the electrodes. The driving signals preferably drive each drive member at its resonant frequency. Preferably the resonant frequencies of the drive members 38 and 40 are identical and are typically about 5 kHz.

The two center drive members 38 and 40 together form a counter–rotational torsionally resonant mechanical oscillator. The two outer rate sensing members 34 and 36 together form a two axis tuned inertial rate sensing element.

Referring to FIGS. 1A, 1B and 6, the central portion 52 of the drive member 38 has a thickness that is less than the thickness of the frame 50. The central portion 150 of the drive member 40 is also thinner than its frame 100. The difference in thickness of the central portions and the frames causes a small gap to exist between the central portions when the frame 50 of the drive members 38 and the frame 100 of the drive member 40 are bonded together.

Referring to FIGS. 1A, 1B and 6, the rate sensing members 34 and 36 have sensing elements 110 and 112, respectively. The rate sensing member 34 includes a central portion 120 and a plurality of compliant leaf springs 122–125 that extend from the central portion 120 to the sensing element 110. Similarly, the rate sensing member 36 has leaf springs 130–

133 that extend from its central portion 121 to the sensing element 112. The sensing element 112 is preferably formed as a generally thin rectangular structure that has a generally rectangular central opening 113. The central portion 121 is thicker than the sensing element 112, which is thicker than the leaf springs 130–133 as may be seen in FIGS. 1B and 6.

FIG. 6 indicates the structure resulting from bonding the drive members 38 and 40 together and then bonding the rate sensing members 34 and 36 to the central portions of the back surfaces of the drive members 38 and 40, respectively. Only the thickest central portions 120 and 121 of the rate sensing members 34 and 36, respectively are bonded to the corresponding drive members 38 and 40. The leaf springs 121–125 and 130–133 are thus free to oscillate with small amplitude along the Z–axis as seen in FIGS. 1A and 1B and in the plane of the paper as seen in FIG. 6.

Referring to FIGS 1 and 6, after the drive members 38 and 40 and the rate sensing members 34 and 36 are bonded together, they are placed in the base 22 so that the corners of the drive members 38 and 40 contact the base mounts 24–27. The base mounts 24–27 preferably are each formed to comprise a damped compliant element between the mechanical oscillator support base 22 and frame 50 of the drive member 38. This compliant element is necessary to insure that the counter–rotational mechanical oscillator has a single resonant frequency. The compliant element also provides the additional benefit of attenuating external vibration inputs.

When the rotation sensor 20 is fully assembled and drive voltages are applied to the electrode assemblies of both drive members 38 and 40, the rotation sensor 20 is ready for use in detecting rotations about in–plane axes labeled X and Y in FIG. 1A. A rotation input about the X or Y axis produces out of plane oscillations in the rate sensing elements 110 and 112. These out of plane oscillations are caused by out–of–plane Coriolis forces that are generated on an object that is oscillating in the plane by rotation of the object about an axis in the plane. The leaf springs 122–125 and 130–133 allow an appropriate amount of out–of–plane oscillation about the in–plane axis in response to input rotations. The two rate sensing members 34 and 36 preferably have X axis resonant frequencies

that are substantially equal. Similarly, the Y axis resonant frequencies of the rate sensing members 34 and 36 preferably are the same. These resonant frequencies are preferably equal to the oscillating frequency of the drive member.

The out of plane oscillations caused by input rotation rates about either the X or Y axis cause the relative displacements between the drive members 38 and 40 and the corresponding rate sensing members 34 and 36 to change. These changing displacements are seen as changes in capacitance, which provides a capacitive pickoff that is explained subsequently.

In FIGS. 1A and 6 the central portion of the drive member 40 is indicated by the reference numeral 150. The drive member 40 is also indicated as having flexure beams 152 and 154 that correspond to the flexure beams 61 and 63, respectively, of the drive member 38.

FIG. 7 schematically illustrates the capacitive signal pickoff. An oscillator 160 provides a reference excitation signal to the rate sensing members 34 and 36. The reference excitation may have a voltage of about 10 volts and a frequency of about 250 kHz. Capacitors 162 and 164 are formed between the drive member 38 and the rate sensing member 34. Capacitors 166 and 168 are formed between the drive member 40 and the rate sensing member 36. A drive voltage of about +10 volts is applied to the capacitors 162 and 166. A drive voltage of about −10 volts is applied to the capacitors 164 and 168. Electrical leads 170–173 carry the oscillatory signals that indicate the rotation rate to signal processing circuitry discussed below.

Referring to FIG. 8, in its basic form the signal processing receives the sensor inputs that consist of signals indicative of rotation rates about the X and Y axes for both rate sensing members 34 and 36. The sensor inputs are provided to first and second X axis sensor capture loop circuits 200 and 202, respectively and to first and second Y axis sensor capture loop circuits 204 and 206, respectively. The outputs of the first and second X axis sensor capture loop circuits 200 and 202, respectively, are input to a summer 208. Similarly, the outputs of the first and second Y axis sensor capture loop circuits 204 and 206, respectively, are input to a

summer 210. The summer 208 and 210 then provide the X and Y axis rotation signals to a quantizer 212.

The sensor circuits 200–206 may be identical. A structure for each of four sensor circuits 200–206 is shown in FIG. 9. The angular rate input signal and a signal indicative of in-phase dynamic errors are combined in a summer 220. The output of the summer 220 represents an input that is dynamically modulated by Coriolis generated forces from the counter-rotational driving oscillations at frequency ω_D. These in-phase signals can be arbitrarily referenced as a cosine function of the drive signal. A signal indicative of quadrature dynamic errors can then be characterized as a sine function of the drive signal. The blocks 222 and 224 represent the dynamic modulation of the input rate signals at he oscillation frequency. The sum of the signals from the blocks 222 and 224 are represented by a summer 226.

The output of the summer 226 is input to circuitry represented by a block 228 that represents the sensor element response to the angular rate input. The output of the block 228 is then amplified by an amplifier 230. The amplifier 230 provides outputs to a pair of demodulators 232 and 236 that demodulate the signal with cos $\omega_D t$ and sin $\omega_D t$, respectively. The outputs of the demodulators 232 and 233 are input to corresponding servo compensation circuits 234 and 233, respectively. The signal output of the servo compensation circuit 234 is the angular rate signal that is sent to the appropriate summer 208 or 210 of FIG. 8. The signals output from the servo compensation circuits 234 and 236 are also input to torquing modulator circuits 238 and 240 that modulate the signals input thereto with cos $\omega_D t$ and sin $\omega_D t$, respectively. The signals output from the torquing modulator circuits 238 and 240 are input to a summer 242. The output of the summer 242 is then fed into the sensing element torquing electrodes 227a–227d to provide feedback torque to the sensing element through summer 226.

FIG. 10 illustrates signal processing circuitry in which signals from both sensing elements are combined in one capture loop. An X rate input signal to the block 252 is shown being modulated by Coriolis forces at the drive frequency ω_D. The output of block 252 is represented by an input to

the torquing summer 250. Pickoff circuits 254 and 256 generate amplitude responses of the first and second rate sensing members 34 and 36 at the frequency ω_D. Amplifiers 260 and 262 amplify signals output from the circuits 254 and 256, respectively. A summer 264 produces a signal indicative of the sum of the signals output from the circuits 254 and 256, and a summer 266 produces a signal indicative of the difference of the signals output from the circuits 254 and 256. The sum and difference signals are then input to a demodulator 270 that performs in-phase and quadrature demodulation. The output of the demodulator 270 is input to a servo compensation circuit 272, which then produces the measured rate of rotation about the X axis.

A signal from the driven members' servo oscillator 274 is connected to the demodulator 270 and to a modulation and summing circuit 276 that provides in-phase and quadrature torque modulation and summing. The modulation and summing circuit 276 receives signals from the servo compensation circuit 272 and provides a feedback torquing signal to the summer 250.

The circuit of FIG. 10 includes a second section 280 for the Y axis that has the same components as described above for the X axis. In FIG. 10 the signals from both members are summed and differenced before the feedback torques are applied. This approach enhances the Q of the output axis tuning. If each sensing member were independently captured the Q would be attenuated by not allowing the feedback torques to be phase-locked in a counter-oscillating mode where the reaction torques for each member balance against each other. Energy would be dissipated in the base mount if each member was captured independently. To completely capture the sensor deflections both the in-phase and quadrature signals must be nulled, as well as the sum and difference signals. The signal representing rate is the in-phase component of the differenced signal. The other feedback torques correct for common mode and quadrature torques from undesirable cross-coupled inputs and angular acceleration inputs.

The detailed performance and environmental requirements for the rotation sensor 20 are: bias Repeatability of 0.01°/hr; Scale Factor Error of

20 PPM; Angle Random Walk of 0.001°/√hr; and a sensitivity of less than 0.01°/hr/G.

There are several significant and unique features to the rotation sensor 20 according to the present invention which reduce vibration rectification errors and improve bias repeatability. First, common mode rejection of linear vibration for both axes is achieved by having the centers of gravity of the sensing elements coincident with their centers of suspension. Also their is no concern for the matching and tracking of the phase and gain of independent acceleration sensors as used in other mechanizations of vibrating rate sensors. Second, the inertial rate sensing element is mechanically isolated from out of plane drive forces which introduce bias error. Third, the drive motion does not develop any relative motion between the inertial rate sensing element and its pickoff because each drive member and its associated sensing element move together as a single unit. Fourth, the torsional mechanical oscillator assembly is counter balanced, which minimizes the sensitivity to variations in external mechanical impedances which can also lead to bias errors.

The mechanical oscillator provides the necessary vibratory velocity excitation for two axis Coriolis angular rate sensing. The spring constant of the four flexure elements 60–63 and the inertias of the oscillating elements 52 and 34 coupled with the other four flexure elements of the drive member 40 and the inertias of the oscillating elements 36 and 150 establishes the oscillator resonant frequency, while the peak velocity amplitude is sensed by the oscillator pickoff and controlled by the drive electronics applying signals to the drive electrodes on the opposing surfaces of the oscillating plates. On the opposite surfaces of the oscillating plates are the pickoff/forcer electrodes used to force rebalance each axis of the inertial rate sensing element. It should be noted that all drive, pickoff/forcer electrodes and electrical contacts are confined to the mechanical oscillator.

The natural frequency of the mechanical oscillator is on the order of five kilohertz with the resonant frequency of the total rotation sensor chip and the base mount compliant elements on the order of one kilohertz. The desired bandwidth of five hundred hertz can therefore be met easily.

In operation, the upper rate sensing member 36 and lower rate sensing member 34 are driven 180° out of phase by the mechanical oscillator elements 38 and 40. The upper and lower rate sensing members of the rate sensing element respond to the input of an angular rate about an axis perpendicular to the axis of the mechanical oscillator by oscillating about an axis perpendicular to both the input axis and the mechanical oscillator. Components of this Coriolis induced oscillation of the rate sensing element are sensed by the X and Y axis capacitive pickoffs. These pickoff signals are applied to the X and Y channels of the rotation sensor servo electronics which feeds back voltages to electrostatically force the rate sensing element to null. The magnitude of the voltage feed back on each axis are linearly proportional to the X and Y components of the input angular rate.

The signal processing circuitry servoes both the in-phase and quadrature signals in a manner that allows the loop to have integral gain at the mechanical oscillator frequency ω_D while providing a DC signal proportional to the angular rate.

Referring to quantizer 212 in FIG. 8, a dual range conversion approach with high speed over-sampling is employed. A high dynamic range, fourth order delta-sigma modulator converts the analog rate signal to a serial bit stream, each bit representing a delta theta. These delta thetas are then summed and sampled by the processor at 5 kHz, a factor of 10 higher than the bandwidth, and high speed averaging performed. Since the signal contains noise this process results in enhanced resolution. A fine range of 180°/sec with resolution after over-sampling of 1.5 arc–sec is achieved. The coarse range is increased by 4 time to 720°/sec and 6.0 arc–sec resolution.

The evaluation of this rotation sensor uses basically the same theory, and has the same transfer function, as the tuned rotor gyro (TRG). The Q of the sensing element oscillation is analogous to the TRG dynamic time constant, and the difference between the drive frequency and the sensor output natural frequency is equivalent to the TRG spin speed being different than its tuned speed.

A few of the important features of this invention are discussed below. The sensor 20 operates in a closed loop mode, which allows the sensing axes to be tuned, and thereby reduces the random walk by orders of magnitude over open-loop devices. The random walk of an open loop tuning-fork gyro, for example, degrades in proportion to its bandwidth, since the pickoff sensitivity continues to decrease as it is tuned further away from the fork's vibration frequency to achieve higher bandwidth.

The driving forces do not act directly on the sensitive elements. Driving the sensitive element directly would be analogous to mounting the motor of a TRG directly on the rotor element, instead of driving through the shaft and gimbal structure. For the case where the sensitive element itself is driven there will be a direct source of bias error if the driving force for the vibration is misaligned by even the slightest amount in the direction of the Coriolis sensing axis. The phase of this cross-coupled force is identical to that generated by a rate input and therefore cannot be distinguished from an actual rate input. This force will vary with time and temperature if the pressure, alignment, or hysteresis losses change. Even for designs in which the sensor is driven through a suspension the normal forces can be transmitted to the sensing elements if the stiffness in this sensing axis direction is not high. This would be the case for designs which apply "surface" micromachining methods because no "depth" can be achieved in the suspension to give high stiffness in the cross-plane direction.

The oscillating drive motion, or its resulting stress, does not appear at the pickoff. A complete elimination of one of the most damaging error sources is accomplished by having the base of the displacement pickoff move with the sensing element. This feature totally removes the coherent coupling of the imperfections on the oscillating surface of the sensitive elements as they oscillate over the pickoff. Even though the surface finish of the micromachined silicon is on the order of .02 microinches it is still many orders of magnitude greater than the amplitude of motion required to be resolved for 0.01 deg/hr performance. This moving pickoff technique also eliminates effects due to any nominal tilt of the sensitive element during micromachining. The signal from such a tilt would couple into the

output proportional to the product of the tilt and the angular oscillation amplitude. In many other Coriolis sensing devices the pickoff uses piezoresistive, or piezoelectric stress-sensing transducers for detecting the Coriolis forces. Unfortunately these pickoffs must decouple the full stress of the driven oscillation, which is many billions of times greater than the stress required to resolve 0.01 deg/hr.

The present invention provides inherent common mode rejection of linear vibration. Each sensing element is inherently balanced such that its center of gravity is at its center of suspension. They are not cantilevered as in most other designs. As such, no output is generated for linear vibration inputs. For cantilevered proof masses the signals from two outputs are differenced to reject the sensitivity to vibration. This means that very good gain and phase matching is critical for such cancellation.

For a 5000 Hz resonant frequency and a peak velocity of .5 meters/sec, the peak Coriolis acceleration is .005 micro-G for .01°/hr input rate. The peak output axis displacement for this acceleration at 5000 Hz is 5.1×10^{-11} microns. For a conservative Q value of 500 about the output axis, this motion will amplify to 2.5×10^{-8} microns. A pickoff with a nominal gap of 10 microns will generate 1.2 nV for a 5 volt bridge source and an estimated stray and back-plane capacitance of as much as 5 times the gap capacitance. This yields a scale factor of 120 nV per °/hr. With present day instrumentation amplifiers having better than 4 nV/√Hz of noise, the rotation sensor white noise would be better than 0.05 deg./hr/√Hz, with allowance for conversion to RMS and full wave demodulation. This noise converts to better than 0.001 deg/√hr of random walk. If higher Q's are attained, then this number will decrease proportionally.

In operation the Coriolis forces generated when a rate is applied about an axis perpendicular to the axis of oscillation will coerce the sensitive elements to angularly vibrate out of plane. Signals from pickoffs mounted on the plates adjacent to the sensing elements measure these motions, are amplified, and then used to generate feedback torques to cancel the effect of the Coriolis forces. The torque required to keep the sensing elements at null is a measure of the input rate.

rotational oscillations of the second drive member central portion are transmitted to the sensing member central portion; and

a sensing portion connected to the sensing member central support member to allow the sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the sensing portions; and

signal processing apparatus connected to the sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portion.

2. The rotation sensor of claim 1, further comprising a plurality of flexure beams connected between the frame and drive member central portion.

3. The rotation sensor of claim 1, further comprising a plurality of generally planar leaf spring members connected between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are perpendicular to the planes of the leaf spring members.

4. The rotation sensor of claim 3, further comprising a capacative pickoff formed on the sensing portion such that the out-of-plane oscillations of the sensing portion produce capacitance changes in the capacitive pickoff.

5. The rotation sensor of claim 1, further comprising a plurality of generally planar leaf spring members connected between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are perpendicular to the planes of the leaf spring members.

6 The rotation sensor of claim 5 further comprising a capacative pickoff formed between the sensing portion and the plurality of electrodes such that the out-of-plane oscillations of the sensing portion produce capacitance changes in the capacitive pickoff.

7. The rotation sensor of claim 5, further comprising a plurality of base mounts connected between the base and the frame of the drive member, each base mount being formed to comprise a damped compliant element for providing a single mechanical resonant frequency in the rotation sensor and for attenuating external vibration inputs.

8. The rotation sensor of claim 5 wherein the signal processing apparatus comprises:

a first summing circuit connected to the capacitive pickoff and arranged to receive signals indicative of the input rotation rate;

a first modulation circuit connected to the first summing apparatus and arranged for modulating the input rotation rate signal with a signal indicative of the cosine of the drive signal frequency;

a second modulation circuit arranged for modulating quadrature dynamic errors with a signal indicative of the sine of the drive signal frequency;

a second summing circuit connected to add signals output from the first and second modulation circuits and provide feedback signals to the drive member;

a first demodulator circuit connected to the capacitive pickoff for demodulating the sensor element response signal with the cosine of the drive frequency;

a first compensation circuit connected to receive signal output form the first demodulator circuit;

a second demodulator circuit connected to the capacitive pickoff for demodulating the sensor element response signal with the sine of the drive frequency;

a second compensation circuit connected to receive signal output form the second demodulator circuit;

a first torquing modulator circuit connected to the first compensation circuit;

a second torquing modulator circuit connected to the second compensation circuit; and

a third summing circuit for adding signals output from the first and second torquing modulator circuits, the third summing circuit producing a

feedback signal that is input to the plurality of electrodes of the drive member.

9. The rotation sensor of claim 1 wherein the signal processing apparatus comprises:

a first summing circuit arranged to receive signals indicative of the input rotation rate;

a first modulation circuit connected to the first summing apparatus and arranged for modulating the input rotation rate signal with a signal indicative of the cosine of the drive signal frequency;

a second modulation circuit arranged for modulating quadrature dynamic errors with a signal indicative of the sine of the drive signal frequency;

a second summing circuit connected to add signals output from the first and second modulation circuits and provide feedback signals to the drive member;

a first demodulator circuit connected to the sensing portion for demodulating the sensor element response signal with the cosine of the drive frequency;

a first compensation circuit connected to receive signal output form the first demodulator circuit;

a second demodulator circuit connected to the sensing portion for demodulating the sensor element response signal with the sine of the drive frequency;

a second compensation circuit connected to receive signal output form the second demodulator circuit;

a first torquing modulator circuit connected to the first compensation circuit;

a second torquing modulator circuit connected to the second compensation circuit; and

a third summing circuit for adding signals output from the first and second torquing modulator circuits, the third summing circuit producing a feedback signal that is input to the plurality of electrodes of the drive member.

10. A rotation sensor, comprising:

a base;

a first drive member mounted to the base and formed of a first single, silicon wafer having a first pair of oppositely-facing planar surfaces, the first drive member including:

a first frame;

a first drive member central portion connected to the first frame and arranged to have rotational compliance between the first frame and the first drive member central portion about an axis perpendicular to the planar surfaces of the first silicon wafer; and

a first plurality of electrodes formed on at least one side of the first central portion;

a first drive signal apparatus for applying drive signals having a drive signal frequency to the first plurality of electrodes, the first plurality of electrodes being arranged such that the drive signals cause rotational oscillation of the first drive member central portion about a drive axis perpendicular to the planar surfaces of the silicon wafer;

a first silicon sensing member that includes:

a first sensing member central support member connected to the first drive member central portion such that rotational oscillations of the first drive member central portion are transmitted to the first sensing member central portion; and

a first sensing portion connected to the first sensing member central support member to allow the first sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the first sensing portion;

a second drive member mounted to the first drive member and formed of a second single, silicon wafer having a second pair of oppositely-facing planar surfaces, the second drive member including:

a second frame;

a second drive member central portion connected to the second frame and arranged to have rotational compliance between the second frame and the second drive member central portion about an axis perpendicular to the planar surfaces of the second silicon wafer, the first and second drive member central portions being connected together in facing relationship; and

a second plurality of electrodes formed on at least one side of the second central portion;

a second drive signal apparatus for applying drive signals having a drive signal frequency to the second plurality of electrodes, the second plurality of electrodes being arranged such that the drive signals cause rotational oscillation of the second drive member central portion about a drive axis perpendicular to the planar surfaces of the silicon wafer;

a second silicon sensing member that includes:

a second sensing member central support member connected to the second drive member central portion such that rotational oscillations of the second drive member central portion are transmitted to the second sensing member central portion; and

a second sensing portion connected to the second sensing member central support member to allow the second sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the second sensing portion; and

signal processing apparatus connected to the first and second sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portions.

11. The rotation sensor of claim 10 wherein the first and second sensign portions are arrnaged to oscillate in opposite direcitons in response to an input rotation rate.

12. The rotation sensor of claim 12 wherein each of the first and second drive members comprises a plurality of flexure beams connected between the frame and drive member central portion.

13. The rotation sensor of claim 12 wherein each of the first and second sensing portions comprises a plurality of generally planar leaf spring members connected between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are perpendicular to the planes of the leaf spring members.

14. The rotation sensor of claim 13, further comprising:

a first capacative pickoff formed on the sensing portion, such that the out-of-plane oscillations of the first sensing portion produce capacitance changes in the first capacitive pickoff; and

a second capacative pickoff formed on the sensing portion, such that the out-of-plane oscillations of the second sensing portion produce capacitance changes in the second capacitive pickoff.

15. The rotation sensor of claim 10, further comprising:

a first plurality of generally planar leaf spring members connected between the first sensing member central support member and the first sensing portion such that the out-of-plane oscillations in the first sensing portion are perpendicular to the planes of the first leaf spring members; and

a second plurality of generally planar leaf spring members connected between the second sensing member central support member and the second sensing portion such that the out-of-plane oscillations in the second sensing portion are perpendicular to the planes of the second leaf spring members.

16. The rotation sensor of claim 15 further comprising:

a first capacative pickoff formed between the first sensing portion and the first plurality of electrodes, such that the out-of-plane oscillations

of the first sensing portion produce capacitance changes in the first capacitive pickoff; and

a second capacative pickoff formed between the second sensing portion and the second plurality of electrodes, such that the out-of-plane oscillations of the second sensing portion produce capacitance changes in the second capacitive pickoff.

17. The rotation sensor of claim 15, further comprising a plurality of base mounts connected between the base and the frame of the first drive member, each base mount being formed to comprise a damped compliant element for providing a single mechanical resonant frequency in the rotation sensor and for attenuating external vibration inputs.

18. The rotation sensor of claim 10 wherein the signal processing apparatus comprises:

a first amplifier connected to the first sensign portion to amplify rotation response signals output therefrom;

a second amplifier connected to the second sensign portion to amplify rotation response signals output therefrom;

first summing circuit connected to the first and second amplifiers and arranged to produce a sum signal indicative of the sum of the amplified rotation signals;

a second summing circuit connected to the first and second amplifiers and arranged to produce a difference signal indicative of the difference of the amplified rotation signals;

a modulation circuit connected to the first and second summing circuits for providing in-phase and quadrature phase modulation of the sum and difference signals;

a servo compensation circuit connected to the modulation circuit for receiving in-phase and quadrature phase modulated sum and difference signals therefrom and producing a measured rate signal for input rotation about a first axis;

an in-phase and quadrature phase torque modulation and summing circuit connected to the servo compensation circuit to receive signals therefrom;

an oscillator servo connected to the in-phase and quadrature phase torque modulation and summing circuit and to the in-phase and quadrature phase demodulation circuit for providing automatic gain control; and

a third summing circuit connected to the an in-phase and quadrature phase torque modulation and summing circuit for receiving a modulated signal therefrom;

19. A method for forming a rotation sensor, comprising the steps of:

providing a base;

forming a drive apparatus by a method comprising the steps of:

forming a first drive member from a single, silicon wafer having a first pair of oppositely-facing planar surfaces by forming a first frame that is mounted to the base, forming the first drive member to further include a first drive member central portion connected to the frame such that there is rotational compliance between the frame and the central portion about an axis perpendicular to the planar surfaces of the silicon wafer, and forming a first plurality of electrodes on at least one side of the first drive member central portion;

forming a second drive member from a single, silicon wafer having a second pair of oppositely-facing planar surfaces by forming a second frame that is mounted to the base, forming the second drive member to further include a second drive member central portion connected to the frame such that there is rotational compliance between the frame and the central portion about an axis perpendicular to the planar surfaces of the silicon wafer, and forming a second plurality of electrodes on at least one side of the second drive member central portion;

mounting the second drive member frame to the first drive member frame

applying drive signals having a drive signal frequency to the plurality of electrodes;

arranging the electrodes of the first and second drive members such that the drive signals cause rotational oscillation of the first and second drive member central portions about a drive axis perpendicular to the planar surfaces of the first and second silicon wafers;

providing a silicon sensing member that by a process that includes the steps of:

connecting a sensing member central support member to the drive member central portion such that rotational oscillations of the drive member central portion are transmitted to the sensing member central portion; and

connecting a sensing portion to the sensing member central support member to allow the sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the sensing portions; and

connecting signal processing apparatus to the sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portion.

20. The method of claim 19 further comprising the step of connecting a plurality of flexure beams between the frame and drive member central portion.

21. The method of claim 19, further comprising the step of connecting a plurality of generally planar leaf spring members between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are perpendicular to the planes of the leaf spring members.

22. The method of claim 3, further comprising a capacative pickoff formed on the sensing portion, such that the out-of-plane

oscillations of the sensing portion produce capacitance changes in the capacitive pickoff.

23. The method of claim 19, further comprising the step of connecting a plurality of generally planar leaf spring members between the sensing member central support member and the sensing portion such that the out-of-plane oscillations in the sensing portion are perpendicular to the planes of the leaf spring members.

24 The method of claim 19 further comprising the step of connecting a capacative pickoff between the sensing portion and the plurality of electrodes, such that the out-of-plane oscillations of the sensing portion produce capacitance changes in the capacitive pickoff.

25. The method of claim 19, further comprising the steps of:

connecting a plurality of base mounts between the base and the frame of the drive member; and

forming each base mount to comprise a damped compliant element for providing a single mechanical resonant frequency in the rotation sensor and for attenuating external vibration inputs.

26. The method of claim 6 wherein the signal processing step comprises the steps of:

connecting a first summing circuit to the capacitive pickoff to receive signals indicative of the input rotation rate;

connecting a first modulation circuit to the first summing circuit for modulating the input rotation rate signal with a signal indicative of the cosine of the drive signal frequency;

providing a second modulation circuit arranged for modulating quadrature dynamic errors with a signal indicative of the sine of the drive signal frequency;

providing a second summing circuit to add signals output from the first and second modulation circuits and provide feedback signals to the drive member;

connecting a first demodulator circuit to the capacitive pickoff for demodulating the sensor element response signal with the cosine of the drive frequency;

providing a first compensation circuit to receive signal output form the first demodulator circuit;

connecting a second demodulator circuit to the capacitive pickoff for demodulating the sensor element response signal with the sine of the drive frequency;

providing a second compensation circuit to receive signal output form the second demodulator circuit;

connecting a first torquing modulator circuit to the first compensation circuit;

connecting a second torquing modulator circuit to the second compensation circuit; and

providing a third summing circuit for adding signals output from the first and second torquing modulator circuits, to produce a feedback signal that is input to the plurality of electrodes of the drive member.

27. The method of claim 19 wherein the signal processing step comprises the steps of:

connecting a first summing circuit to the capacitive pickoff to receive signals indicative of the input rotation rate;

connecting a first modulation circuit to the first summing circuit for modulating the input rotation rate signal with a signal indicative of the cosine of the drive signal frequency;

providing a second modulation circuit arranged for modulating quadrature dynamic errors with a signal indicative of the sine of the drive signal frequency;

providing a second summing circuit to add signals output from the first and second modulation circuits and provide feedback signals to the drive member;

connecting a first demodulator circuit to the capacitive pickoff for demodulating the sensor element response signal with the cosine of the drive frequency;

providing a first compensation circuit to receive signal output form the first demodulator circuit;

connecting a second demodulator circuit to the capacitive pickoff for demodulating the sensor element response signal with the sine of the drive frequency;

providing a second compensation circuit to receive signal output form the second demodulator circuit;

connecting a first torquing modulator circuit to the first compensation circuit;

connecting a second torquing modulator circuit to the second compensation circuit; and

providing a third summing circuit for adding signals output from the first and second torquing modulator circuits, the third summing circuit producing a feedback signal that is input to the plurality of electrodes of the drive member.

28. A method for forming a rotation sensor, comprising the steps of:

providing a base;

forming first drive member of a first single, silicon wafer having a first pair of oppositely-facing planar surfaces, by a method that includes the steps of:

providing a first frame;

connecting a first drive member central portion to the first frame

arranging the first drive member to have rotational compliance between the first frame and the first drive member central portion about an axis perpendicular to the planar surfaces of the first silicon wafer; and

forming a first plurality of electrodes on at least one side of the first central portion;

mounting the first drive member to the base;

applying drive signals having a drive signal frequency to the first plurality of electrodes, the first plurality of electrodes being arranged such that the drive signals cause rotational oscillation of the first drive member central portion about a

drive axis perpendicular to the planar surfaces of the silicon wafer;

forming a first silicon sensing member by a method that includes:

connecting a first sensing member central support member to the first drive member central portion such that rotational oscillations of the first drive member central portion are transmitted to the first sensing member central portion; and

connecting a first sensing portion to the first sensing member central support member to allow the first sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the first sensing portion;

mounting a second drive member that is identical to the first drive member on the first drive member

applying drive signals having signal frequency to the second drive member to produce oscillations about the drive axis perpendicular to the planar surfaces of the silicon wafer;

mounting a second silicon sensing member identical to the first sensing member on the second drive member: and

processing signals output from the first and second sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portions.

29. The method of claim 28 including the step of arranging the first and second sensign portions to oscillate in opposite direcitons in response to an input rotation rate.

30. The method of claim 29 including the step of forming the first and second drive members to comprise a plurality of flexure beams between the frame and drive member central portion.

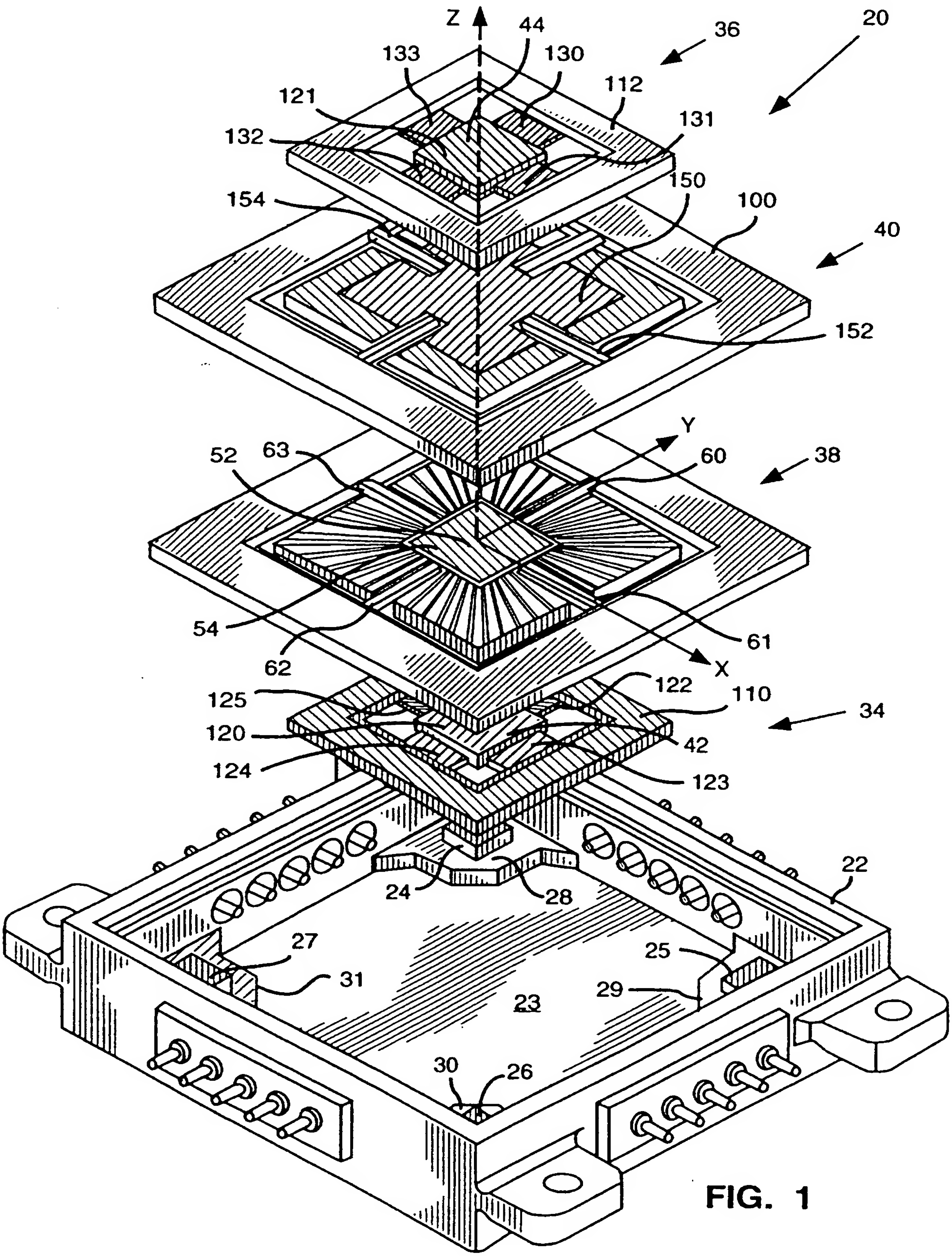

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FIG. 1

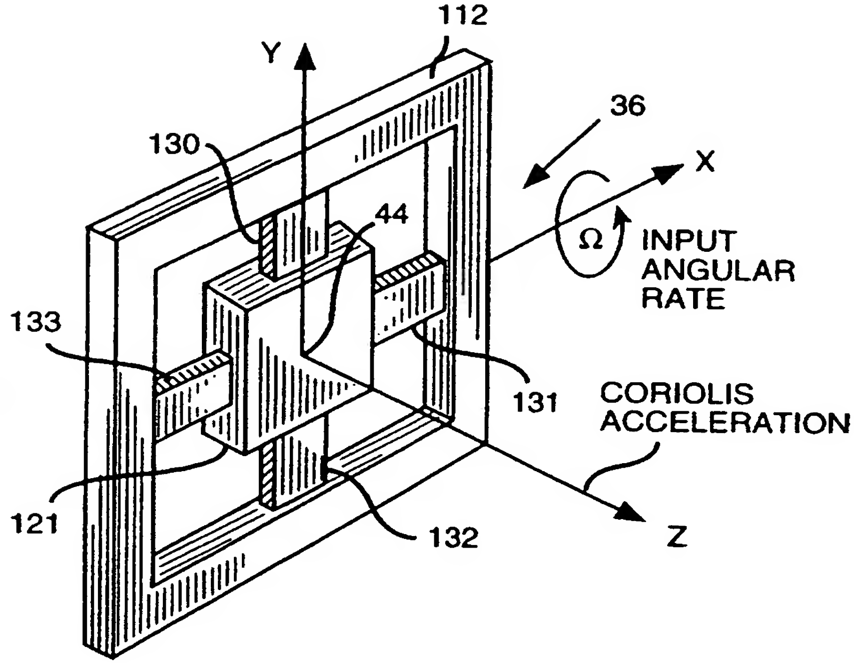

FIG. 1B

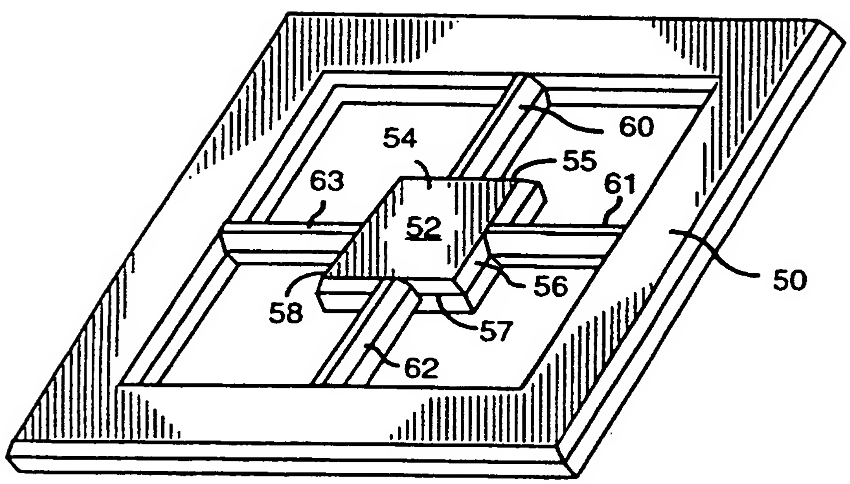

FIG. 2

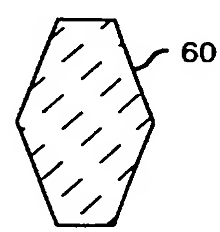

FIG. 3

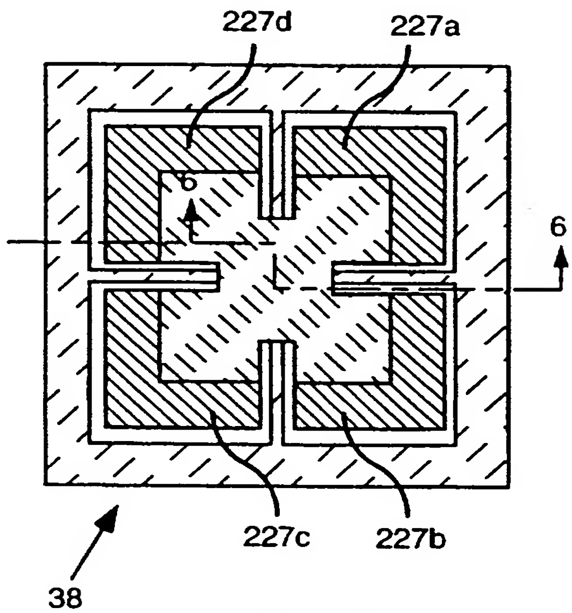

FIG. 4

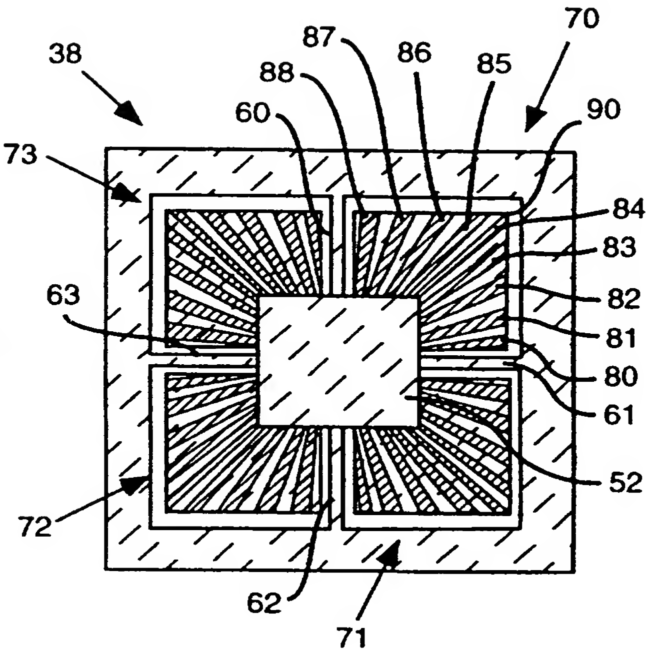

FIG. 5

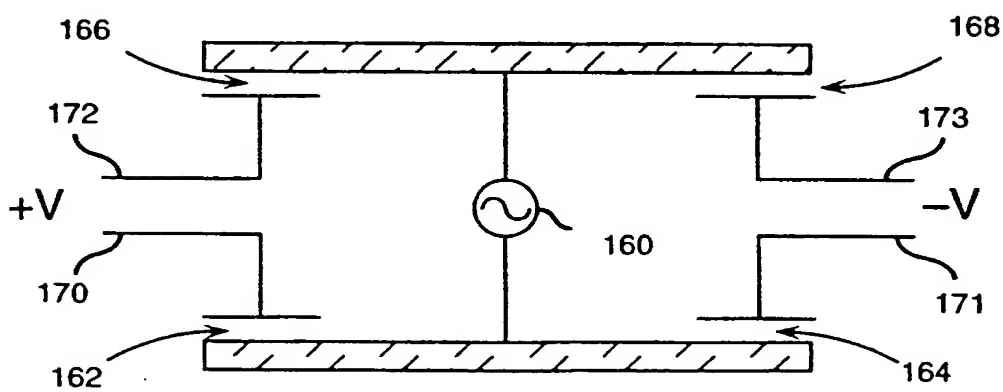

FIG. 7

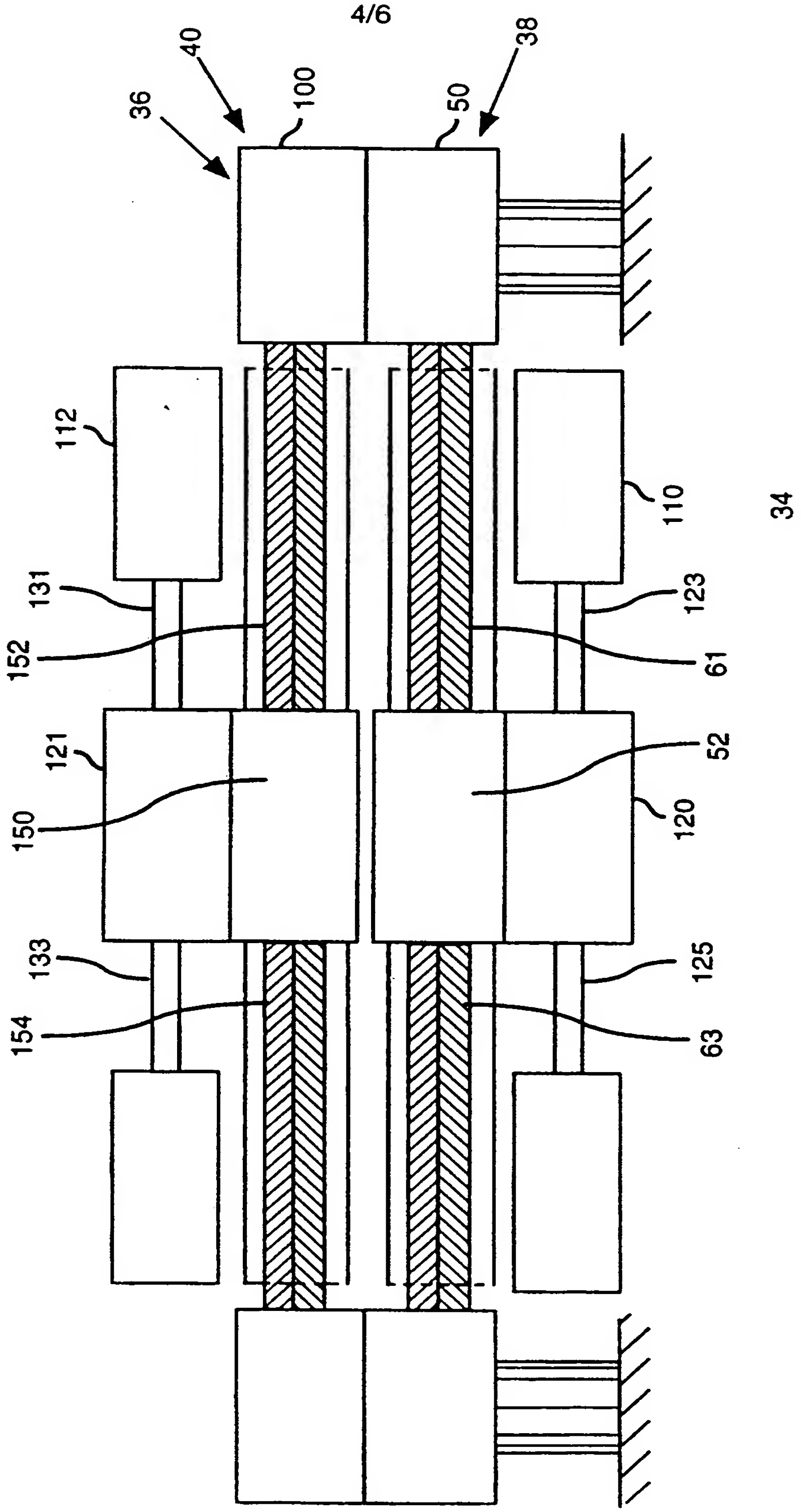
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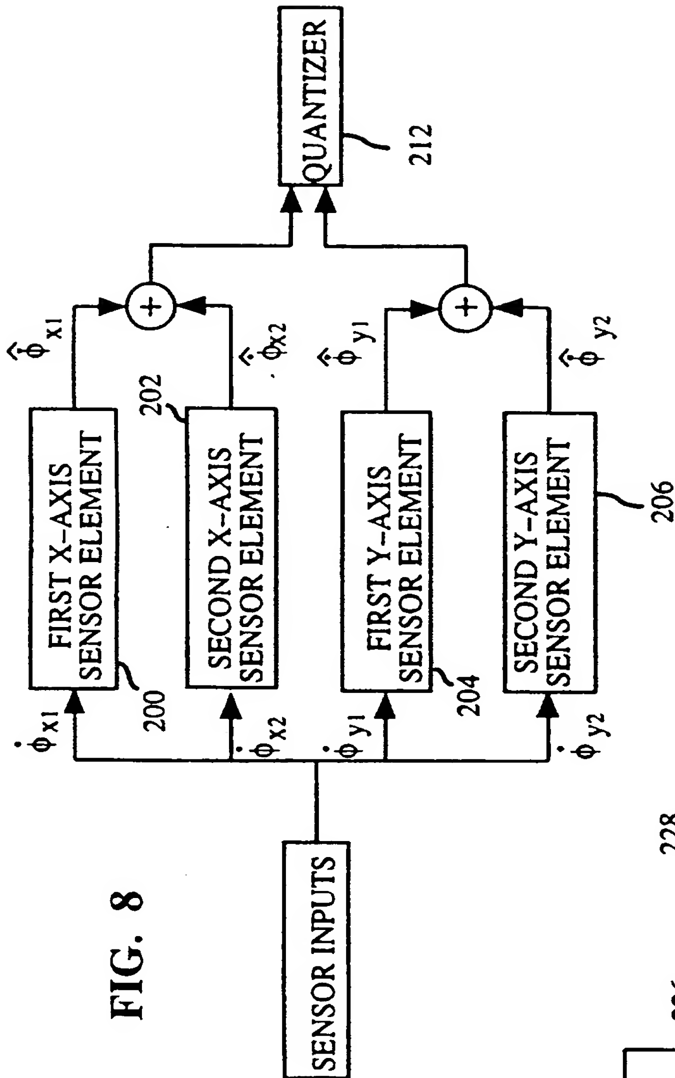
FIG. 6


QUANTIZER
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SECOND X-AXIS SENSOR ELEMENT
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FIRST Y-AXIS SENSOR ELEMENT
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SECOND Y-AXIS SENSOR ELEMENT
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SENSOR INPUTS
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$\dot{\phi}_{x2}$
$\dot{\phi}_{y1}$
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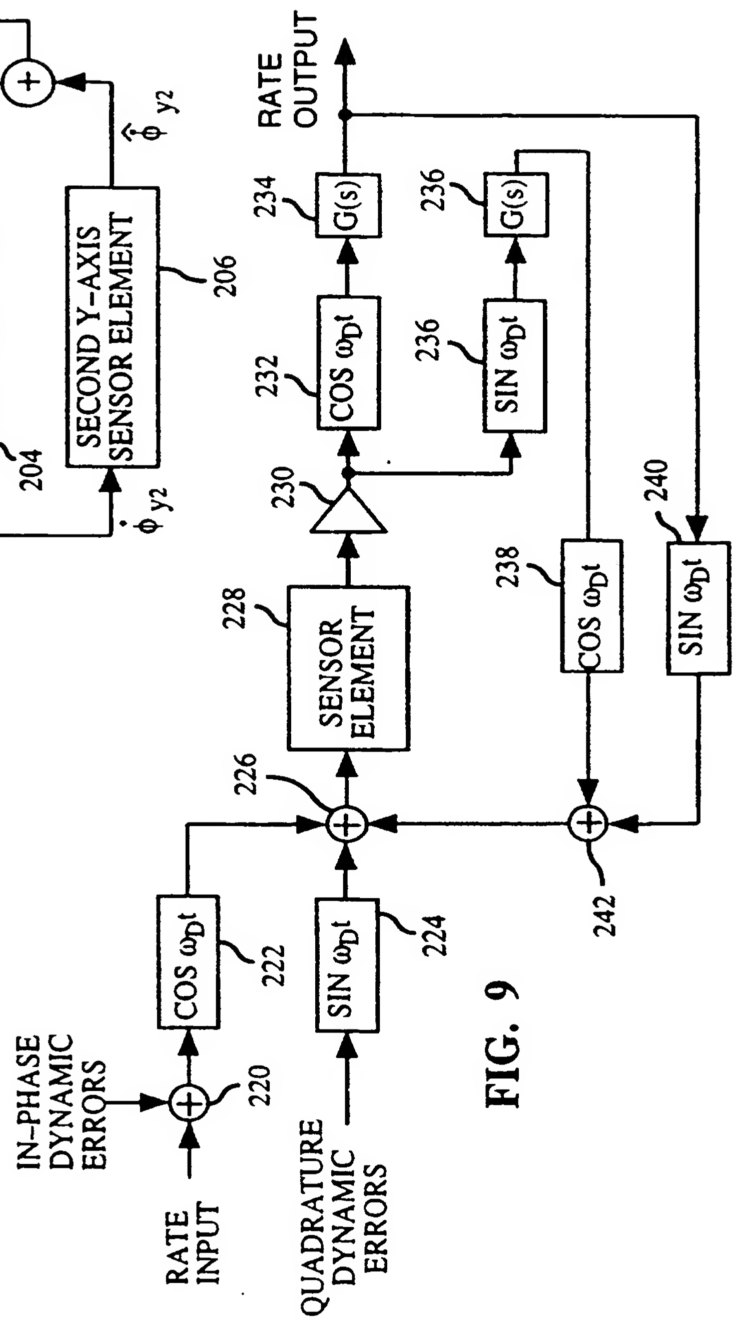
FIG. 8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QUADRATURE DYNAMIC ERRORS
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SENSOR ELEMENT
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COS $\omega_D t$
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SIN $\omega_D t$
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G(s)
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RATE OUTPUT
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SIN $\omega_D t$
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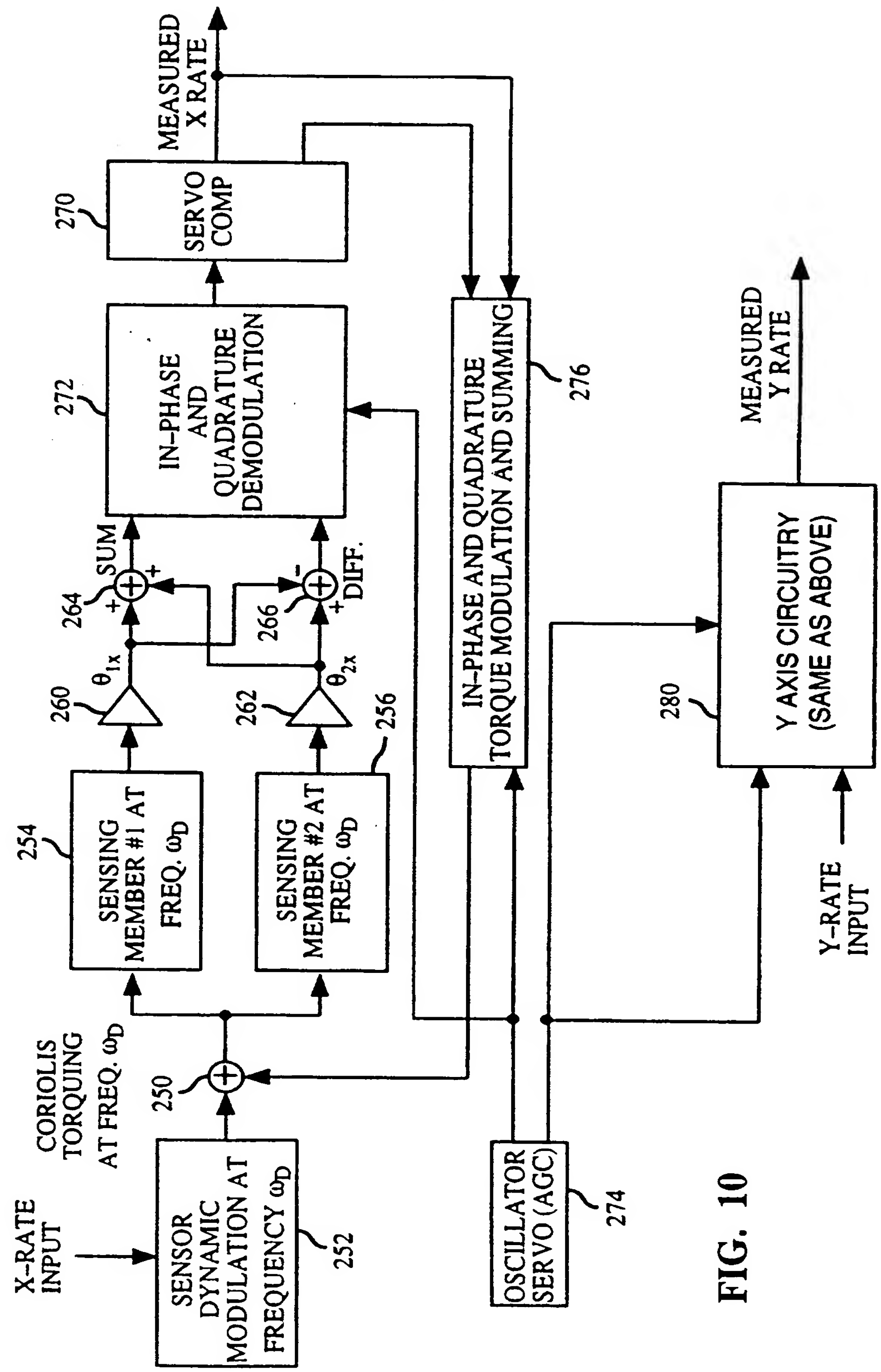
FIG. 9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SERVO COMP
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IN-PHASE AND QUADRATURE TORQUE MODULATION AND SUMMING
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MEASURED Y RATE
SUM
DIFF.
264
266
θ_{1x}
θ_{2x}
260
262
256
Y AXIS CIRCUITRY (SAME AS ABOVE)
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254
SENSING MEMBER #1 AT FREQ. ω_D
SENSING MEMBER #2 AT FREQ. ω_D
Y-RATE INPUT
CORIOLIS TORQUING AT FREQ. ω_D
250
X-RATE INPUT
SENSOR DYNAMIC MODULATION AT FREQUENCY ω_D
252
OSCILLATOR SERVO (AGC)
274

FIG. 10

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(81) Designated States: AM, AT, AU, BB, BG, BR, BY, CA, CH, CN, CZ, DE, DK, EE, ES, FI, GB, GE, HU, JP, KE, KG, KP, KR, KZ, LK, LR, LT, LU, LV, MD, MG, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SI, SK, TJ, TT, UA, US, UZ, VN, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG), ARIPO patent (KE, MW, SD, SZ, UG).

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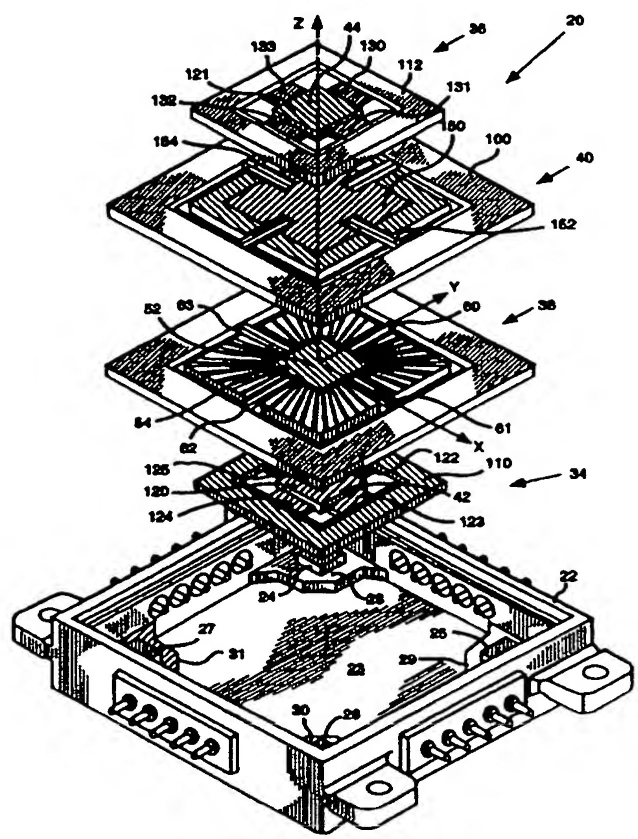
(54) Title: TWO AXIS NAVIGATION GRADE MICROMACHINED ROTATION SENSOR SYSTEM

(57) Abstract

A two axis closed loop angular rate sensor which provides a digital delta theta output signal. A drive member is formed of a single, silicon wafer having a pair of oppositely-facing planar surfaces. The drive member includes a frame and a drive member central portion connected to the frame and arranged to have rotational compliance between the frame and the central portion about an axis perpendicular the planar surfaces of the silicon wafer. Drive signals are applied to a plurality of electrodes on the central portion to cause rotational oscillation of the drive member central portion about a drive axis perpendicular to the planar surfaces of the silicon wafer. A silicon sensing member is connected to the drive member. The sensing member has a central support member connected to the drive member central portion such that rotational oscillations of the drive member central portion are transmitted to the sensing member central portion. A sensing portion is connected to the sensing member central support member to allow the sensing portion to oscillate about the drive axis and to allow an input rotation rate about an axis perpendicular to the drive axis to produce out-of-plane oscillations of the sensing portions. Signal processing apparatus is connected to the sensing portion for producing a signal indicative of the input rotational rate as a function of the amplitude of the out-of-plane oscillations of the sensing portion.



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INTERNATIONAL SEARCH REPORT

Intern al Application No
PCT/US 95/09533

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01C19/56

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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A	US,A,5 313 835 (DUNN WILLIAM C) 24 May 1994 see the whole document -----	1

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☒ Patent family members are listed in annex.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
19 January 1996	29. 01. 96

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 95/09533

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
GB-A-2113842	10-08-83	NONE	
US-A-5313835	24-05-94	NONE	